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Design methodology to investigate contact fatigue damage in turbine engine hardware

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Abstract

One of the most significant maintenance drivers in current turbine engines is contact fatigue damage where turbine blades are inserted into the disk. This is commonly referred to as the dovetail slot. The stress state at the dovetail slot is difficult to determine with standard finite element analysis because of the nonlinear nature of the contact problem. Because of this, a design methodology based on singular integral equation analysis has been developed. This design methodology is used for the first time to compare the contact stress behavior of similar components from two different turbine engines. The use of singular integral equation methods to analyze these components is supported by a similar analysis on a dovetail experimental fixture. Stress predictions by the singular integral equation method compare well to finite element methods for static stress conditions in a dovetail slot. Additionally, the results from the component analysis indicate that there is a correlation between stress state and damage seen during maintenance. However, details concerning the correlation still need to be resolved.

Keywords: Fretting; Contact fatigue; Dovetail; Integral equation

1. Introduction

The requirements for modern aircraft turbine engines are typically dictated by the form, fit and function of the given application. High level requirements are things such as thrust capacity, specific fuel consumption, size and weight. The United States Air Force (USAF) has a large number of aircraft with different engine variants that meet form, fit and function requirements. Variants can be evolutions of the same original designs or completely different engines from different companies. This variety causes challenges with configuration control, logistics and maintenance. One maintenance concern that often arises with different engine types is that different engines can require completely different maintenance techniques. This is despite the fact that the engine variants may be flying on the same aircraft with the same mission. In addition to different maintenance protocols, certain components on a given engine may have a problematic feature, while a variant may have no problems with that component. This type of problem is not uncommon.

One damage mechanism that has an affect on all turbine engines is wear. Wear damage can take the form of standard wear, galling or fretting. Each of these wear types, when severe enough, can necessitate the early retirement of components. The various forms of wear damage cause enough early retirement that the USAF has conducted a significant amount of research over the past 5 years dedicated to wear mitigation. A significant result of this research has been, in part, the development and implementation of a computer code based on Singular Integral Equations (SIE) that has enabled the accurate and rapid determination of contact stress in turbine engine components [1,2]. This code has already been transitioned to industry [3], but has yet to be used by the USAF to address engine life on legacy components.

The following study details aspects of the first attempt to apply singular integral equation analysis to address maintenance concerns of two similar engine components. These components are two separate compressor disk spools. The spools bear a number of similarities. They both are made of titanium. They are used in the two different engines

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with the same form, fit and function. They have approximately the same scheduled maintenance. They both are the first two stages of the compressor, fourth and fifth total stages of the engine. Both engines have 13 total stages. These engines fly on the same aircraft and perform the same mission. Despite these similarities, one component is nearly always retired early due to wear damage while the other is retired only rarely. There are some significant differences in design specifics. Among these are differences in dovetail slot geometry (the area where the blade attaches to the disk), the number of total blades on each disk and the relative tolerance specifications of the spools. The following study examines the differences in contact stresses for each of these two components. The differences in contact stresses are related to differences in contact damage for each of the components. This comparison is supported by stress analysis on an experimental dovetail fixture [4].

2. Background

When the National High Cycle Fatigue (HCF) program began, fretting fatigue damage was identified as one of the most significant problems affecting component life. Further analysis revealed that this statement was too limiting. Contact damage caused in attachment regions is typically referred to as fretting by engine maintenance organizations, but this rarely fits the scientific definition [5,6]. When an engine component is retired for 'fretting,' this generally means contact damage, including wear and galling, as well as fretting. Often attachment regions are subjected to a wide range of loading conditions due to variations in engine RPM and vibratory loading. This means that attachment regions can see wear, galling and fretting all during a single mission. Attempting to resolve the primary damage mechanism is prohibitively complex, so the HCF program has chosen to focus on contact stress prediction and correlation of crack initiation and growth methods to failure life. This emphasis has resulted in improvements in industry design systems, but it has had little impact on legacy components.

This study applies the SIE method to two separate USAF engine components. Each component has significantly different wear characteristics. The contact stresses are determined using the SIE method. Hence, a summary of the SIE method [1,2] will only be presented for completeness. The SIE is a two-dimensional method assuming a unit thickness out-of-plan. It simplifies the contact zone for a dovetail by considering an arbitrary profile (e.g. flat contact zone with rounded or cylindrical indenter, which are most appropriate for fretting fatigue problems) in contact with flat half-plan substrate as shown in Fig. 1. The indenter's profile is defined by a function $h(x)$, which represents the gap between the indenter and the substrate. The x is the local coordinate axis along the contact as shown in Fig. 1. Based on the profile function, one can derive the normal traction

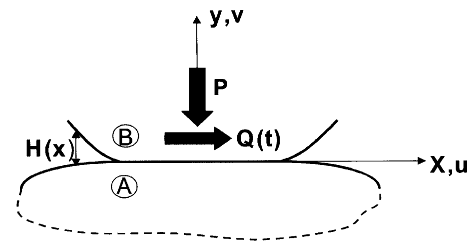

Fig. 1. Indenter profile and fretting contact conditions modeled in the SIE method.

distribution, $p(x)$, on a contact zone of length, L, as [1]

$$\frac{\mathrm{d}h(x)}{\mathrm{d}x} - c_1 = \frac{A}{\pi}\int_L \frac{p(s)}{(x-s)}\mathrm{d}s, \tag{1}$$

where A is a material compliance, and assuming similar plane strain material for contacting bodies it is defined as

$$A = \frac{2}{E}(1-\nu^2), \tag{2}$$

where ν and E are the Poisson's ratio and the Young's modulus. For a symmetric profile with the origin of the axis system at the center of the contact profile the normal force, P, and moment, M, from equilibrium are defines as

$$P = \int_{-a}^{+a} p(x)\mathrm{d}x, \text{ and } M = \int_{-a}^{+a} p(x)x\,\mathrm{d}x, \tag{3}$$

where $x = \pm a$ are the edges of contact for the symmetric contact profile. To solve for the normal traction one can invert Eq. (1) to obtain an analytical solution, however, for a numerical solution trigonometric variable transformation [1] is more computationally efficient. Hence, using the transformations

$$x = a\cos(\phi), \text{ and } s = a\cos(\theta), \tag{4}$$

an expression for the traction distribution, $p(\theta)$, and the slope of the contact surface, $(\mathrm{d}h/\mathrm{d}\phi)$, reduces to

$$p(\theta) = \sum_{n=0}^{\infty} \frac{p_n\cos(n\theta)}{\sin(\theta)}, \text{ and } \frac{\mathrm{d}h}{\mathrm{d}\phi} = \sum_{n=1}^{\infty} h_n\sin(n\phi). \tag{5}$$

Solving the resulting equations, the relationship between h_n and p_n can be expressed as

$$p_1 = \frac{h_1 + C_1 a}{\pi a A}, \quad \text{for } n = 1 \text{ and}$$
$$p_n = \frac{h_n}{\pi a A}, \quad \text{for } n > 1. \tag{6}$$

Considering the boundary conditions in Eq. (3) yield expressions for p_0 and p_1 in term of the normal force and the moment, which are

$$p_0 = \frac{P}{\pi a}, \text{ and } p_1 = \frac{2P(d-e)}{\pi a^2}, \tag{7}$$

where e is the eccentricity between the origin of the local and global coordinate system. Hence, the surface normal